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Optimizing nitrogen fertilizer use for more grain and less pollution

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Abstract

Optimal nitrogen (N) management is critical for efficient crop production and agricultural pollution control. However, it is difficult to implement advanced management practices on smallholder farms due to a lack of knowledge and technology. Here, using 35,502 on-farm fertilization experiments, we demonstrated that smallholders in China could produce more grain with less N fertilizer use through optimizing N application rate. The yields of wheat, maize and rice were shown to increase between 10% and 19% while N application rates were reduced by 15–19%. These changes resulted in an increase in N use efficiency (NUE) by 32–46% and a reduction in N surplus by 40% without actually changing farmers' operational practices. By reducing N application rates in line with official recommendations would not only save fertilizer cost while increasing crop yield, but at the same time reduce environmental N pollution in China. However, making progress towards further optimizing N fertilizer use to produce more grain with less pollution would require managements to improve farmers' practices which was estimated to cost about 11.8 billion US dollars to implement.

Introduction

Producing more food with less pollution is a grand challenge, which is crucial for global sustainable development goals (SDGs)[1,2,3]. With growth and increasing affluence of the global population, the amount of food needed is continually increasing, and a large share of the global population is still suffering from malnutrition, especially in developing economies[4]. Smallholder farming is the prevalent form of agricultural production in these developing economies, satisfying about 40% of global food demand[5]. However, misuse and overuse of fertilizers often occur on smallholder farms, leading to not only a lower crop yield, but also damages to the environment and human health[6]. Agricultural non-point-source pollution has become a dominant contributor to local environmental pressures in many regions of the world. To address these challenges, many best management practices and concepts such as soil testing and 4R stewardship have been developed[7,8], however, they are rarely implemented on smallholder farms due to a lack of knowledge and technological facilities[9].

China is the most populous country in the world. It feeds 18% of global population with only 9% of global cropland area, but is using about 30% of the global synthetic fertilizer production[10,11]. Overuse of fertilizers has led to substantial damages to environmental quality and human health, including eutrophication, air pollution, soil acidification, biodiversity loss and greenhouse gas emission[12,13,14], with very high remedial costs. Chinese governments have, for instance, invested over 45 billion US dollars to control the eutrophication of Lake Tai during the past decade[15]. However, using too much fertilizer in many areas, a large yield gap is still found in China's smallholder agriculture[16]. Soil testing and other advanced agricultural management practices have been proposed to improve agricultural performance. However, the small farm size (<0.5 hectare per household) and low agricultural income share (<20%) inhibit the implementation of such advanced management practices which normally require changes agricultural operational practices[17]. Large-scale farms typically do not have the same constraints as smallholders and can invest more in knowledge and technology, and are therefore higher N use efficiency[6,18]. Therefore, in order to progress the development of large-scale farming, it is crucial to first investigate how to introduce improvements of agricultural management practices.

In this paper we quantify the relationship between N application rate and crop yield across China, based on data from 35,502 on-farm fertilization experiments conducted over a period from 2005 to 2015 (Fig. 1), This assessment has a focus on farmers' practices at national scale and the following key objectives: 1) to quantify the optimal N application rate and related crop yield, N use efficiency (NUE) and N surplus in different regions of China; 2) to estimate the reduction potential of N fertilizer use and how this contributes to crop yield and N loss reduction, without changing farmers' practices; 3) to estimate the economic input and benefits of further optimizing farm management practices.

Results And Discussion

Optimal N rate

Crop yield typically increases with N fertilizer application until a maximum yield level is reached. Beyond this point, a further increase of N application rate will reduce crop yield[19,20]. The economic optimum yields of wheat, maize and rice are estimated at 6.3, 9.0 and 8.1 Mg ha^{-1} with an optimal N application rate of 178, 184 and 170 kg N ha^{-1}, respectively (Fig. 2). The optimal N application rate can achieve the target yield with little damage to economic profits for farmers[21,22]. Under an optimal N rate, the NUE can be as high as 72%, 60% and 73%, and the N surplus 67, 96 and 65 kg N ha^{-1} for wheat, maize and rice, respectively (Fig. 2). With the exception of maize, the N surplus is much smaller than the threshold of N residual in soil derived from the Nitrates Directive[23] (80 kg ha^{-1}). Optimizing N application rate alone can achieve a good performance of crop production using farmers' practices.

Substantial variations of the optimal N application rate and crop yield are found across China[22,24]. Generally, higher optimal N application rates are found in regions with better natural conditions such as high soil fertility and favourable climate, including the North China Plain (NCP) and the Middle-Lower Yangtze Plain (MLYP). Such areas with higher N application rates lead to higher crop yields in these regions, as well as result in a higher NUE and lower N surplus. Relatively lower optimal N application rate and related yields are found in other regions e.g. across Western China, primarily due to lower soil quality and less favourable climate[25,26].

Although a higher yield is found for maize compared to wheat and rice, it has the lowest NUE, and the largest N surplus, with N surplus > 80 kg N ha^{-1} commonly found for maize production in many regions in China (Fig. 3). Some hotspot areas of high N application rates, yield, NUE and N surplus are found scattered across many regions, illustrating the existence of substantial variations of agricultural management at local scale. Meanwhile, NUE above 90% and N surplus below 0 kg N ha^{-1} are also found in some regions, suggesting that soil N mining occurs in these regions, despite a prevalence of excess N fertilizer use (Fig. 3).

Mitigation potential

Compared to farmers' conventional N application rate, strategies aiming to optimize N application can not only lead to a reduction in the application rate of N fertilizers, but also improve crop yield and NUE without changing farmers' practices. The yields of wheat, maize and rice can be increased by 10%, 19% and 13% with an optimal N application rate reduced by 15%, 16% and 19%, respectively. Under such an optimal N rate, NUE can increase by 32%, 46% and 40%, and N surplus decline by 39%, 36% and 48%, respectively (Fig. 4 and Supplementary Table 1).

By optimizing the N application rate, fertilizer cost savings for wheat, maize and rice production of 0.5, 1.0 and 0.8 billion US dollars, and increase grain income by 2.4, 9.1 and 5.8 billion US dollars, respectively could be achieved. From an environmental protection point of view, the overall N surplus of croplands would be reduced by 5.1 Tg N (Fig. 5 and Supplementary Table 2). Such a reduction in the N application rate based on official recommendations would not only achieve fertilizer cost savings and increase crop yield, but also have substantial environmental benefits in China.

Better management

Beyond optimizing N application rates by modifying farmers’ operational practices, further adjustments to management are required as solely achieving an optimal N application rate is only a partial solution to the overall problem. The relationships between N input and N output (harvested N) of the three main crops of China under the optimal N rate are compared with the minimum productivity level (N output = 80 kg ha^{-1}) and ranges for NUE (50%–90%) that suggested by the EU Nitrogen Expert Panel[27] (Fig. 3). Nitrogen use efficiency can reach 50–90% in 67% of wheat producing regions, 54% of maize producing regions and 74% of rice producing regions respectively, of which 40%, 30% and 46% can achieve N surplus less than 80 kg ha^{-1} (Fig. 3). However, 54–70% of the regions producing these three crops have the risks of soil N mining, N pollution and food insecurity with the reasons of insufficient nutrient supplement, volatilization of urea, and improper management. It means that further adjustments to fertilization regimes are required to avoid the risks.

For regions where a risk of soil N depletion is indicated (NUE > 90%), maintaining soil fertility through manure application is required[28,29], with an associated estimated annual cost of 0.9, 0.7 and 0.9 billion US dollars for wheat, maize and rice, respectively (Fig. 5 and Supplementary Table 3). In contrast, in regions where NUE can reach 50-90% while N surplus exceeds 80 kg ha^{-1}, this indicates that N input exceeds N demand of crops and hence substantial N loss occurs. Here, N inputs and losses need to be reduced by applying slow-release N fertilizers[30,31] which incur additional costs of 0.3, 0.4 and 0.3 billion US dollars for wheat, maize and rice, respectively (Fig. 5 and Supplementary Table 4).

Even when achieving an optimal N rate, there are still many regions where NUE remains below 50%, especially for maize (31%). In these areas crop yield per unit area can only be increased and the application of N fertilizer reduced by reasonably increasing planting density and at the same time applying slow-release N fertilizers[31,32], at an additional cost of 0.2, 0.7and 0.1 billion US dollars for wheat, maize and rice, respectively (Fig. 5 and Supplementary Table 5). Regions with an average N output below 80 kg ha^{-1} food security concerns are most prominent, which mostly occurs in the Western China (Fig. 1). Such areas with the problems of inadequate farmland infrastructure (e.g. barren land, sloping land, saline-alkali land and no irrigation facilities)[33,34,35]. Based on the results of high standard farmland construction project in China[36], we need to additional cast 7.3 billion US dollars (wheat: 2.3, maize: 4.7, rice: 0.3 billion US dollars) to improve the farmland infrastructure in the areas where the N output below 80 kg ha^{-1} (Fig. 5 and Supplementary Table 6).

The optimization of fertilization practices (best N management) can increase the yield of wheat, maize and rice by 2%, 6% and 1% while simultaneously reducing the N application rate by 4%, 12% and 5%, respectively, considering an optimal N application rate with farmers’ practices (Fig. 4 and Supplementary Table 1). The optimization of the fertilization practices have a significant effect in maize producing areas, with an increase of NUE by 12%, and a reduction of the N surplus by 31% (Supplementary Fig. 1 illustrates the spatial distribution of N application rates, yield, NUE and N surplus after optimizing fertilization practices). Economic benefits arising from fertilizer cost savings and yield increases can increase revenues by up to 5.2 billion US dollars as a consequence of optimizing fertilization practices. At the same time, these managements reduce the N surplus by 1.7 Tg N (see Fig. 5 and Supplementary Table 2). This means that optimizing N fertilizer use could produce more yield with less pollution.

Methods

On-farm fertilization experiments

Data for a total of 35,502 sites were collected from field trials over the period 2005 to 2015 for main food crops (n = 10,583 for wheat, 15,042 for maize and 9,877 for rice), with sites spread across all agroecological zones in China (Fig. 1). This experiment was designed by the Ministry of Agriculture and Rural Affairs of China to determine the optimal rate of fertilization, which included 3 factors (N, P, K), 4 levels and 14 treatments without replication. In this study, four treatments were selected to calculate the optimal N application rate (RN) of the three crops: (1) no N fertilizer treatment (N_0); (2) low N fertilizer treatment (N_1); (3) Medium N fertilizer treatment (N_2); (4) high N fertilizer treatment (N_3). The N_2 rate was determined by local agricultural extension employees (Staff of the Local Agriculture Bureau and Agricultural Technology Centre that have been uniformly trained) according to their experience and target yield (1.1 times the average yield of the past 5 years), and the rates of N_1 and N_3 were 50% N_2 and 150% N_2, respectively. The average N_2 rates of wheat, maize and rice were 185, 190 and 164 kg ha^{-1}, respectively. Approximately one-third of granular urea was applied at sowing, while the remainder was applied as a topdressing. The rates of P and K fertilizer in each treatment were about 90 kg ha^{-1}, which were applied by broadcasting before sowing. None of these experiments had inputs of animal manure or other organic N sources.

Individual plots were approximately 40 m^2 in size. The management of all experiments, including variety, planting, harvesting, weed and pest control, was undertaken by local farmers according to their experience and based on instructions provided by local agricultural extension employees in a field manual. Upon harvest, a 2.5m × 8m section was harvested from each experimental plot to measure yield. Grain yield weight of wheat, maize and rice was adjusted to a moisture content of 14%, 15.5% and 14%, respectively, and was displayed for all regions in Supplementary Fig. 2.

For each treatment plot, soil properties were examined prior to starting the experiments, and values were determined based on soil samples from a combined sample of 10–20 cores from depths of 0–20 cm. Five stover and grain samples were collected and analyzed separately after harvest. Soil samples were dried and sieved for determining soil organic C content by vitriol acid-potassium dichromate oxidation[37]; representative subsamples were taken to determine pH (1:1 w/v soil/water); total N was determined by the method described by Black[38]; available N (alkaline hydrolyzable) was measured following the procedures described by Lu[39]; available P was determined by the Olsen P method described by Olsen et al.[40] and available K by the method of Shi[41]. To determine the N content, the stover and grain samples were digested with H_2SO_4-H_2O_2 separately, and the concentrations of total N in the digesting solution were measured using the micro-Kjeldahl method[42]. Three subsamples were analyzed for each sample and average values were reported. The climatic data for each experiment site were derived from local weather stations. The data of soil nutrient and climate for each region are shown in Supplementary Fig. 3 and Supplementary Fig. 4, respectively.

Regional distribution of main food crops in China

In this study, on-farm N fertilizer experiments covered 31 provinces and included three grain crops. Based on climate types and planting systems, cropland of China was subdivided into seven principal regions[43], each comprising several provinces, i.e., Northeast region (NE), North China Plain region (NCP), Middle and lower Yangtze River region (MLYR), Southeast region (SE), Southwest region (SW), Northwest region (NW) and others (Supplementary Fig. 5 shows the detailed subregion and crop distribution). For regions summarized under ‘others’ there were no data available and so these regions were not included in the present study, i.e., Taiwan, Hong Kong and Macao.

Estimation of optimal N application rate

In this study, the optimal N application rate was calculated to obtain maximum economic benefits. First, a quadratic regression model was used to assess the grain yield response to N application rate for the 35,502 on-farm N fertilizer experiments using RStudio software (version 3.5.3; RStudio Inc. 2011), showing that yield significantly responded to the N rate ($P < 0.05$)[44]. Next, the following variables were calculated at different N rate: the yield increase (amount above the yield in the N_0 treatment), gross return for the yield increase (yield increase times grain price), cost of N fertilizer (N rate times fertilizer price), and the net return on N application (gross return minus fertilizer cost). Finally, the average net return for each N increment across all N response curves was calculated. The N application rate with the largest average net economic return was defined as the optimal N application rate[45]. In this study, we calculated the optimal N application rate and the corresponding yield, NUE and N surplus based on county (Fig. 2) and regional (Supplementary Fig. 6) scales. The N fertilizer price and market prices of cereal were determined according to the reported by the Ministry of Agriculture and Rural Affairs of the People's Republic of China in 2018-2020: the average price of N fertilizer was \$0.67 kg^{-1} N, and the mean price of wheat, maize and rice grain were \$0.18, 0.15 and 0.21 kg^{-1}, respectively[46].

Nitrogen use efficiency (NUE) and nitrogen surplus (N_{sur})

Nitrogen use efficiency and N_{sur} are important for assessing N management. In this study, the NUE concept focused on the efficiency of all N inputs and represents the efficiency of all N inputs transferring to harvested crop N content. N_{sur} was used to evaluate the balance of N input and output. The main external N input included the following sources: chemical fertilizer, atmospheric deposition, biological N fixation. Minor N inputs (e.g., from irrigation and seed) were not accounted for. The N output includes the N harvested in cereal grain without considering straw, because of the governmental ban on straw burning and economic incentives to return straw since 2000[47,48]. We assumed accordingly that all straw was returned to the field (straw N output was offset by straw N input). Nitrogen use efficiency and N_{sur} are calculated as

$$NUE = N_{har} / (N_{fer} + N_{dep} + N_{fix}) \times 100\% \qquad (1)$$

$$N_{sur} = N_{fer} + N_{dep} + N_{fix} - N_{har} \qquad (2)$$

where N_{har} is the N output by harvested in cereal grain, N_{fer}, N_{dep} and N_{fix} are the N input by chemical fertilizer, atmospheric deposition, biological N fixation, respectively.

The N input from atmospheric deposition is obtained from the seasonal average N deposition summarized by Xu et al.[49] comprising data from 27 rural sites covered by the National Nitrogen Deposition Monitoring Network (NNDMN). There are 2–8 monitoring sites in each region of this study according to the data in NNDMN. Regional N deposition rates were determined as the average of measurements at all sites in each region, and N deposition rates on specific crops per growth season were estimated according to the planting and harvest period of the crops. Nitrogen input from biological N fixation was obtained from Bouwman et al.[50]: the N fixation rate associated with rice production was set to be 25 kg N ha^{-1}, and 5 kg N ha^{-1} for wheat and maize. The average N input for each region is shown in Supplementary Table 7.

We calculated the grain N harvest by grain yield and grain N concentration (if experiments did not determine grain N concentration, the value of N content is derived from Ti et al.[51], at 2.3%, 1.4% and 1.9% of grain N content for wheat, maize and rice, respectively):

$$N_{har} = \text{grain yield} \times \text{grain N concentration} \qquad (3)$$

Evaluation system

The EU Nitrogen Expert Panel[27] proposed an evaluation system for evaluating farmland N management by comprehensively considering N input and output, the NUE, and an N surplus index in a cropping system. Experts believe that the best N management can be achieved with values of N output ≥ 80 kg ha^{-1}, $50\% \leq NUE \leq 90\%$, N surplus ≤ 80 kg ha^{-1}. When the NUE is too high ($NUE > 90\%$), there is a risk of soil consumption mining, and if NUE is too low ($NUE < 50\%$), there is a risk of substantial N losses to the environment and hence pollution. The minimum N output (80 kg ha^{-1}) is set to meet the minimum production level, the maximum N surplus is limited (80 kg ha^{-1}) to avoid substantial N losses. We referred to this evaluation system to evaluate whether the optimal N application rate can meet the best N management.

Economic and environmental benefits

In this study, the economic benefits include two main elements: (1) benefit of cost saving from reduced N fertilizer application; (2) benefit of increasing yield. The environmental benefits were expressed by the reduction of N surplus. The benefits of optimizing N application were estimated by comparing with farmers' conventional fertilizer application practices in China. The overall benefits of the optimization of management practices were estimated by comparing with optimal N application rates. Data on farmers' conventional fertilizer application rates/practices were derived from published literature[52] (Supplementary Table 1). Economic benefits were derived by multiplying N reduction (yield increase) per unit area by the price of fertilizer N (grain) and by the planting area of the crop, in which the planting area of wheat, maize and rice were 2.4, 4.1 and 3.0×10^6 ha^{-1}, respectively (see Supplementary Table 2 for more details)[53]. Different optimization strategies were applied to regions which can not meet all requirements for best N management practices under optimization of N application[54,55] (Supplementary Fig. 7 and Supplementary Table 3,4,5,6 showed the specific optimization measures and implementation costs associated).

Declarations

Data availability

Data supporting the findings of this study beyond those found in the Supplementary Information are available from the corresponding author upon reasonable request.

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Author contributions

Y.D. and B.G. designed the study, K.R., M.X. and Y.D. conducted the research, K.R. and B.G. wrote the first draft, S.R. revised the paper, R.L., L.Z., S.L., H.W. and H.G. collected the data, and all authors contributed to the paper writing, discussion, and revision.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper.

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Figures

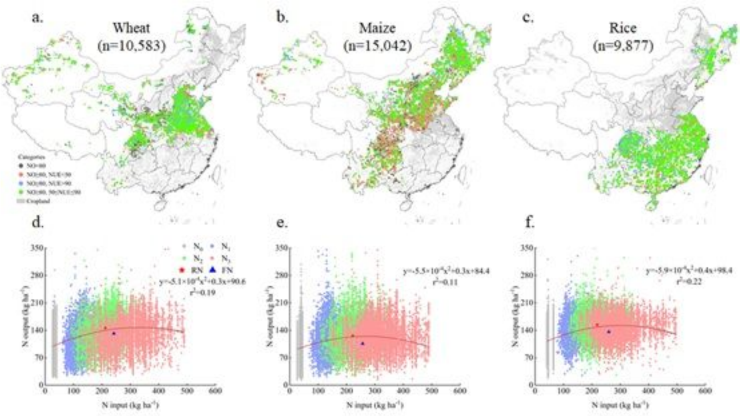

Figure 1

Distribution of fertilization experiments and yield response curves. (a)–(c) regional experimental site distribution of wheat, maize, and rice, respectively; n indicates experimental sites number; NO: nitrogen output (unit: kg ha-1); NUE: nitrogen use efficiency (unit: %). (d)–(f) N yield response to N input for wheat, maize, and rice, respectively. Red squares in (d)–(f) represent optimal N rates (RN); Blue triangles in (d)–(f) represent farmers' conventional fertilizer application rates (FN). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

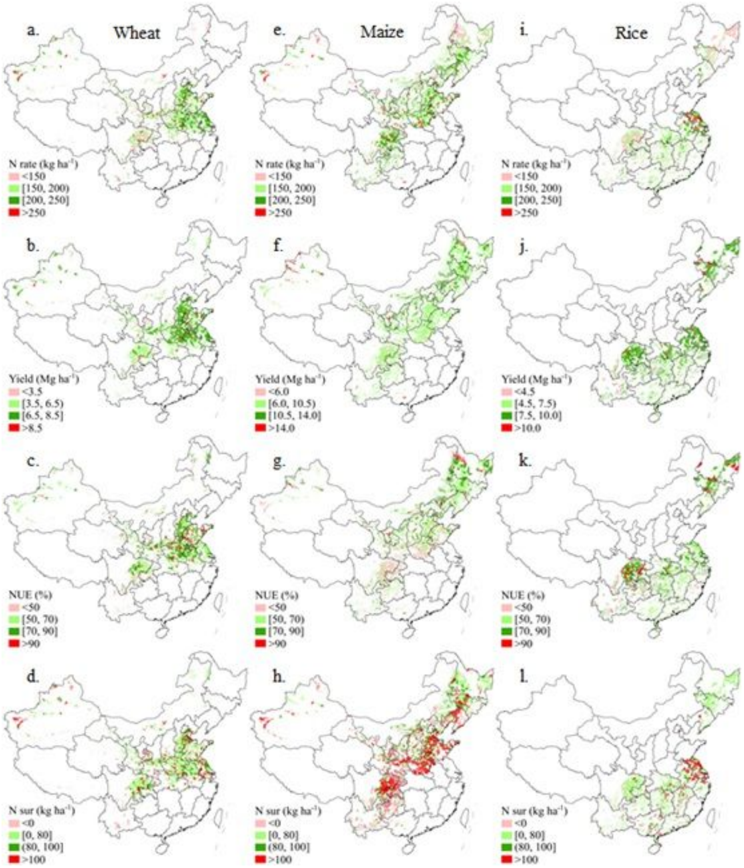

Figure 2

Optimal N application rate (N rate) and corresponding yield, nitrogen use efficiency (NUE) and nitrogen surplus (Nsur) of three grain crops) for wheat (a–d), maize (e–h), and rice (i–l). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

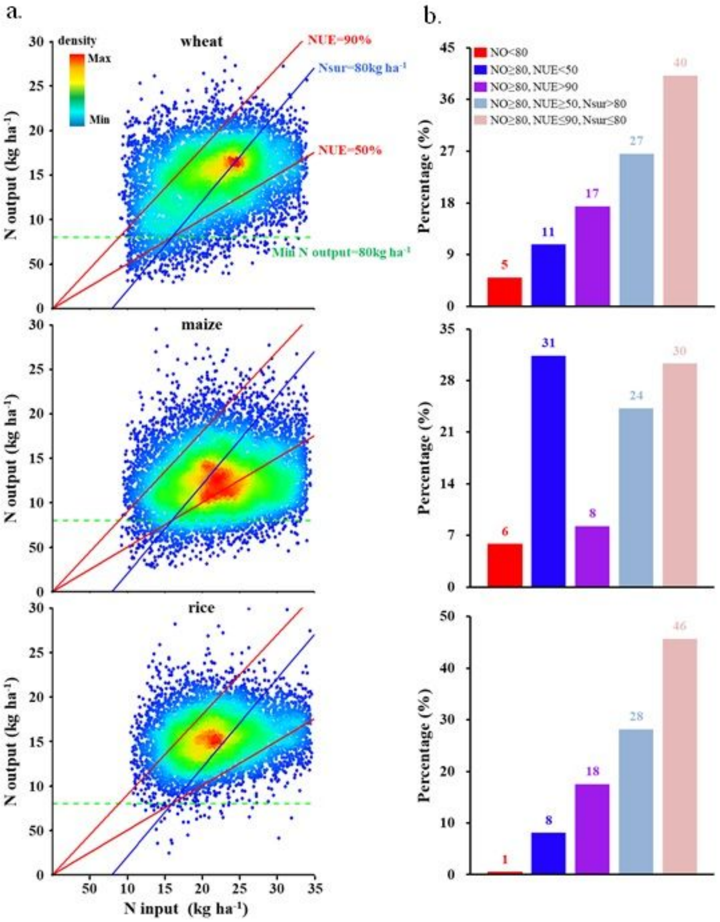

Figure 3

Response of N output to N input under optimal N application rate. NO: nitrogen output (unit: kg ha-1); NUE: nitrogen use efficiency (unit: %); Nsur: nitrogen surplus (unit: kg ha-1). Color of the dots represent the density of dots. Numbers on the top of the bars (b) refer to the percentage of sites in each quadrant (a) to all sites in each crop (wheat: 10,583, maize: 15,042, rice: 9,877).

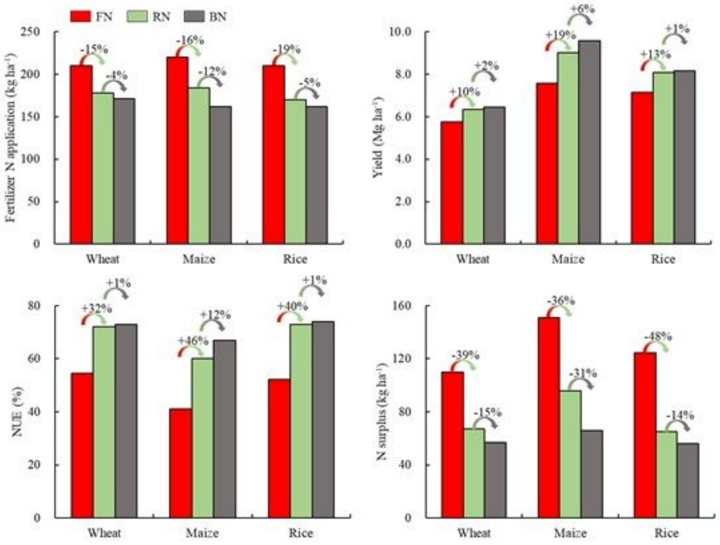

Figure 4

Potential for reduction of nitrogen fertilizer and improvement of nitrogen use efficiency under optimal N rate (RN) and best N management (BN), compared with that under farmers' conventional N application rate (FN).

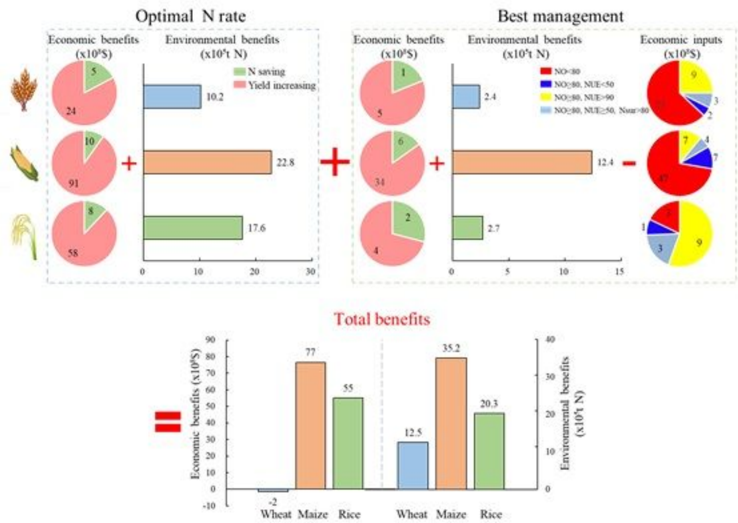

Figure 5

Economic and environmental benefits under optimal N rate and best management. NO: nitrogen output (unit: kg ha-1); NUE: nitrogen use efficiency (unit: %); Nsur: nitrogen surplus (unit: kg ha-1).

Supplementary Files

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- Supplementaryinformation.pdf